Application Note #3414

Sinusoidal Commutation of Brushless Motors

Introduction

This application note includes a complete discussion of brushless motors. Part One is devoted to an in-depth review of both brush- and brushless motor theory. Part Two relates brushless commutation using a Galil Motion Controller. Part Three includes some real-world cases of brushless motor examples, including tips and tricks to maximize the performance of a brushless application.

Part One: Motor Technology

Brush-type motor theory

Basic principles of physics state that a force **F** is generated on a current **I** carrying wire of length **L** when subject to a magnetic field **B** results in equation (1):

$$\mathbf{F = I\,L \times B} \qquad (1)$$

When the magnetic field is always perpendicular to the current vector IL, equation (1) becomes

$$\mathbf{F = I \cdot L \cdot B} \qquad (1a)$$

Consider Figure (1). As shown, a loop of wire with a torque arm **R** is free to rotate about the z-axis. Rotational torque is defined as

$$\mathbf{T = F \cdot R} \qquad (2)$$

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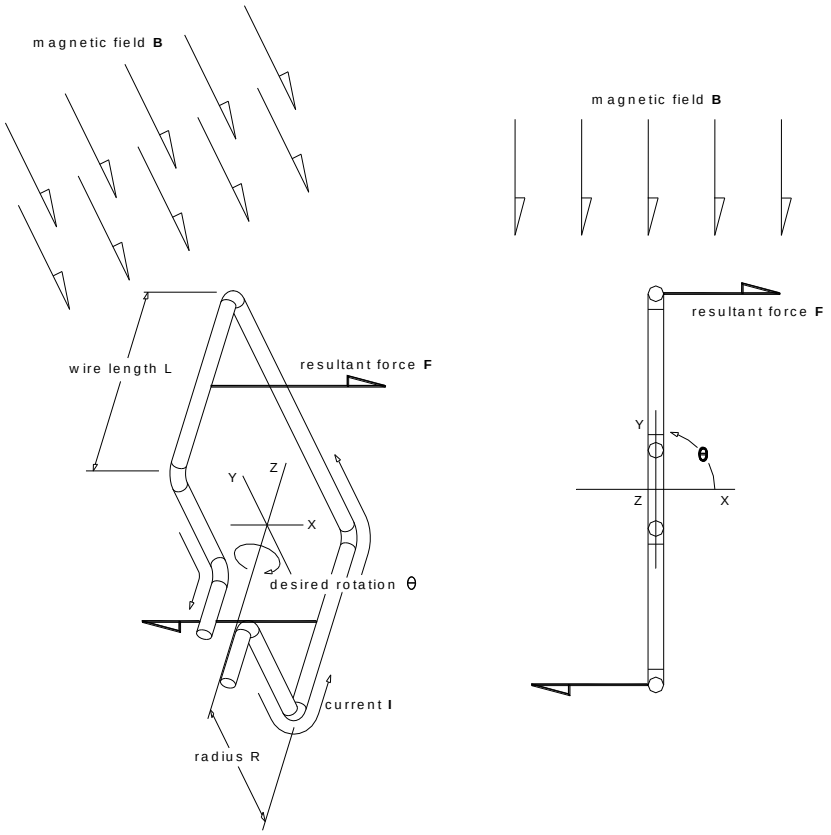

Figure (1) Current-carrying wire exposed to a magnetic field

The resulting torque at the axis of rotation is a function of the angle θ with respect to the magnetic field, or

$$\mathbf{T = F \cdot R} \sin\theta \qquad (3)$$

Substituting equation (1a) into equation (3),

$$\mathbf{T = I \cdot L \cdot B \cdot R} \sin\theta \qquad (4)$$

For a given system, the terms **R**, **B**, and **L** are constants. In terms of a DC motor, these terms can be combined into a common motor constant $\mathbf{K_t}$. This results in equation (5):

$$\mathbf{T = I \cdot K_t \cdot} \sin\theta \qquad (5)$$

As equation (5) shows, the applied torque will decrease as θ approaches 0°. Figure (2) shows the relationship at θ = 45°.

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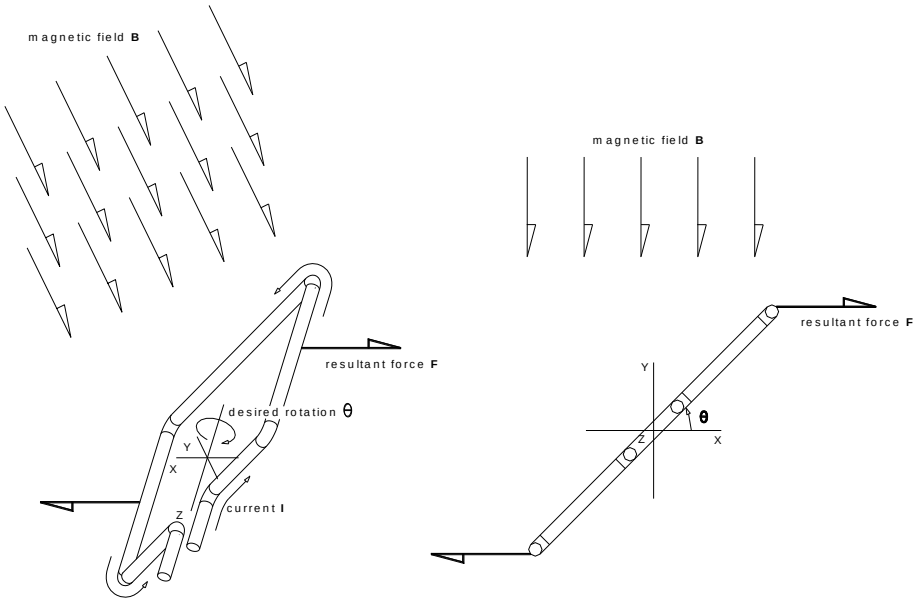

Figure (2) Coil at 45°

At $\theta = 0°$ the torque will be effectively 0. See Figure (3).

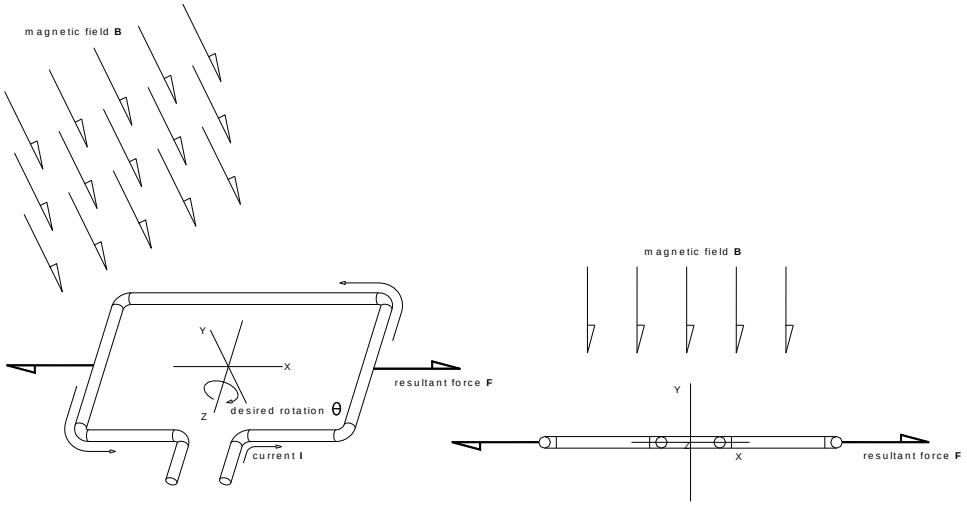

Figure (3) Coil at 0°

If the system has inertia, the coil will drive past 0°, causing the torque to be supplied in the direction opposite of desired. This will cause the system to oscillate around 0°. To avoid this situation, a process known as *commutation* has been developed. Essentially,

a commutator will reverse the direction of current in the coil, providing positive torque at angles larger than 90°. Figures (4a) and (4b) illustrate the principle.

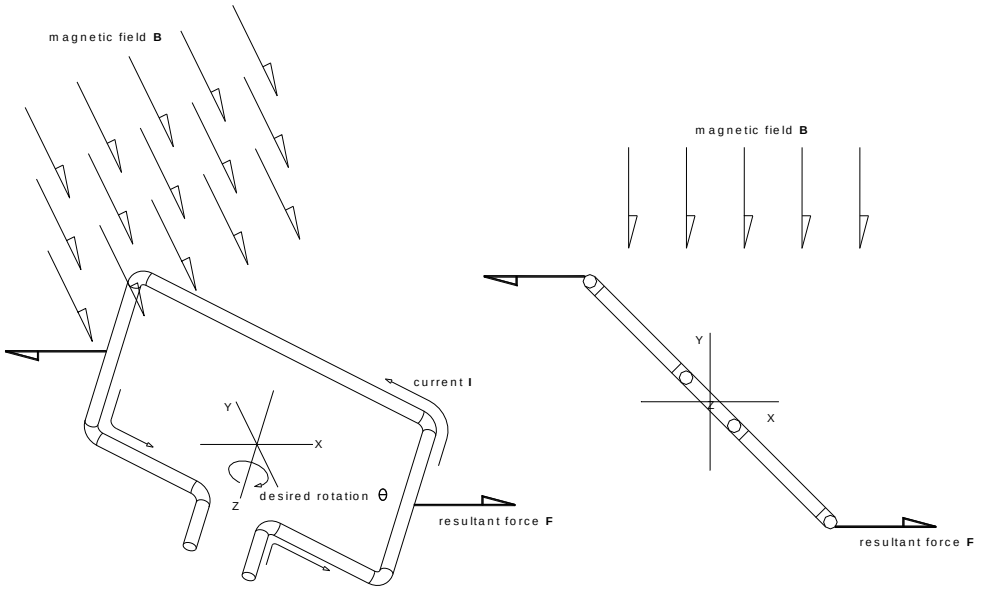

Figure (4a)- Coil beyond 0° - Resultant force is reversed

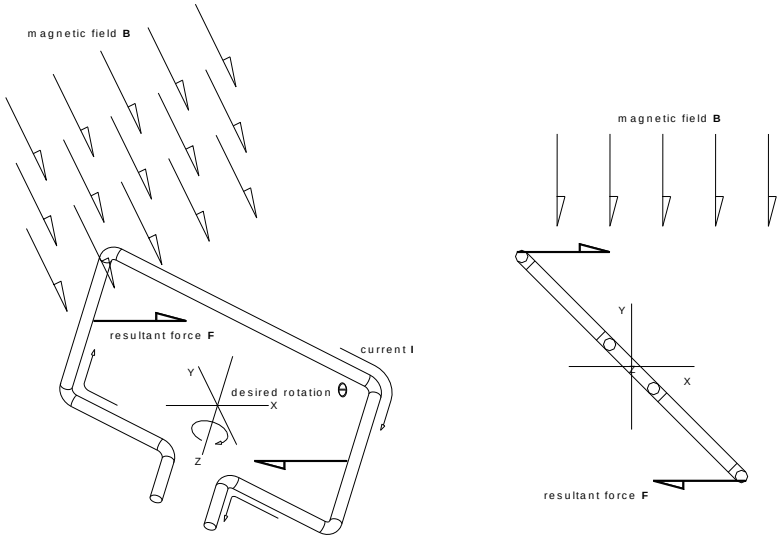

Figure (4b)- Coil beyond 0° - Reversed current; Resultant force OK

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To produce any amount of useable rotational torque, the system design must rely on multiple current carrying coils of wire to be exposed to the magnetic field **B**. Figure (5) shows the physical design of a rotor.

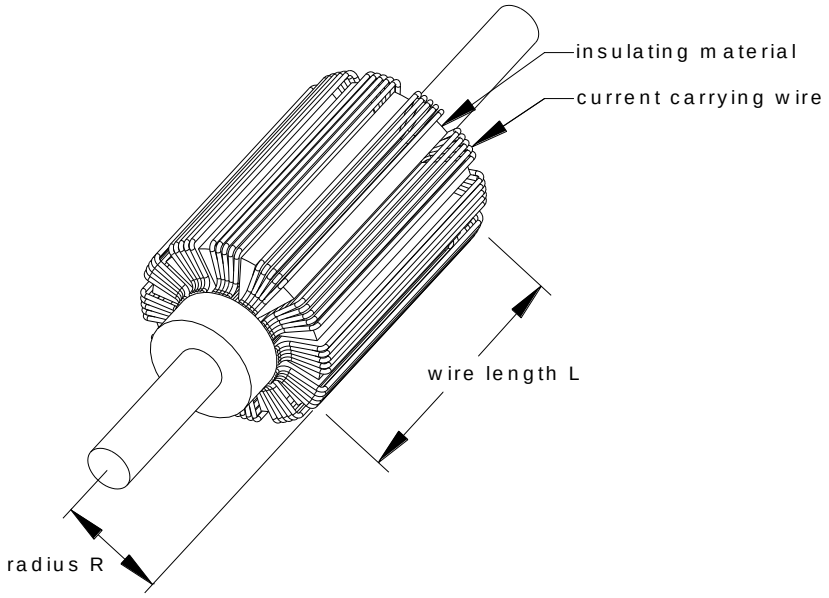

Figure (5)- Basic armature design

In addition to reversing direction of current in the coils, the commutator may also shut off the current in the coil when they are at an angle near 90°, as the torque produced may be too small and represent inefficient operation. To perform such a function, the machine must switch the supply current to these multiple coils based on the rotor angle.

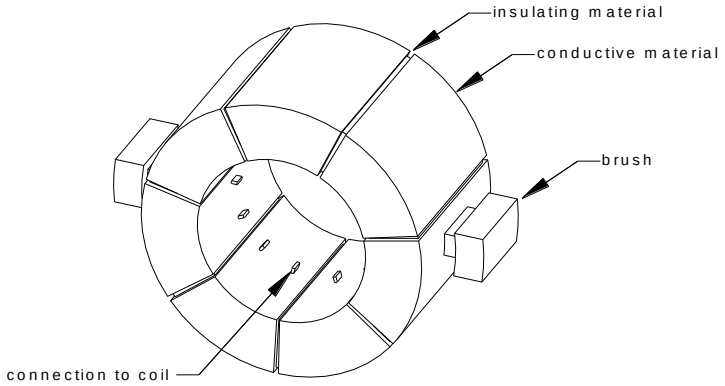

Figure (6)- A simple commutator

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Figure (6) shows the basic elements of a commutator. The machine conductors (which constitute the windings on the armature) are connected in sequence to the segments of the commutator. Figure (7) shows the flow of current through the commutator and armature windings.

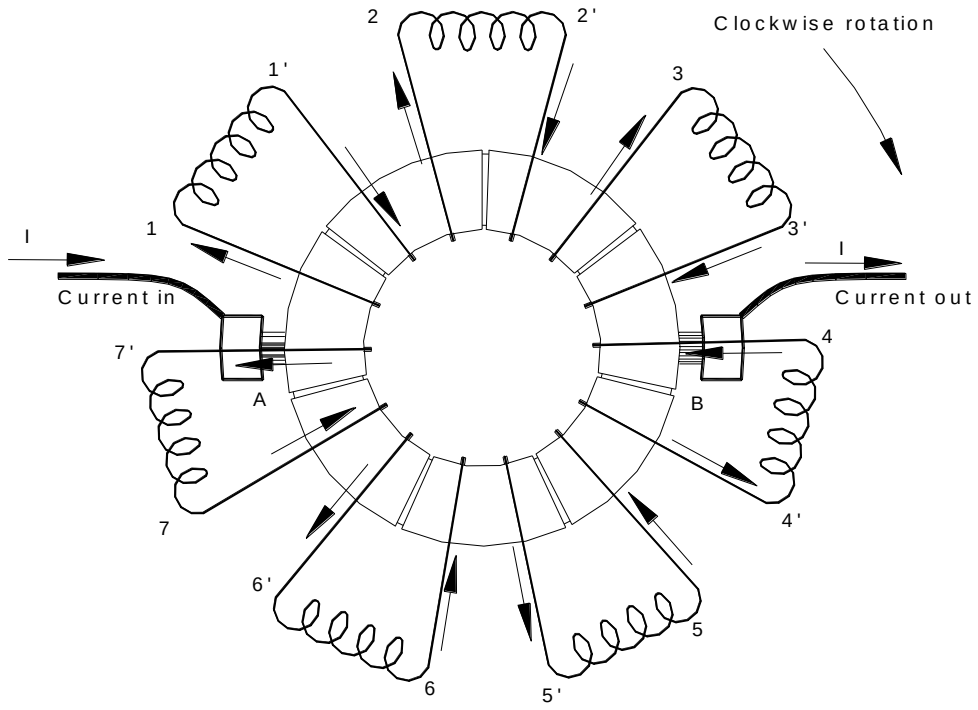

Figure (7)- Current flow through a motor armature

Current flows into the system at brush **A** and flows out at brush **B**. The small arrows indicate current direction in the individual coil sides. If the motor rotation is clockwise, it can be seen that 1/7 of a revolution after the instant shown, the current in coils 3-3' and 7-7' will have changed direction. As the commutator continues to turn, the brushes pass over successive segments, causing the direction of current flow to change. At some points in the armature rotation, the brush will be in contact with two segments. At this condition, the coil connected to these two segments will be shorted through the brush. As a result of this switching, the current flow in the armature occupies a fixed position in space, independent of rotation.

Due to the action of the motor commutator, the armature can be thought of as a wound core with an axis of magnetization fixed in space. The axis of magnetization is determined by the rotary position of the brushes. For a motor to have equal characteristics for both directions of rotation, the axis of magnetization, or brush axis,

must be at an angle of 90° with respect to the magnetic field. Figure (8) shows the resultant axis of magnetization.

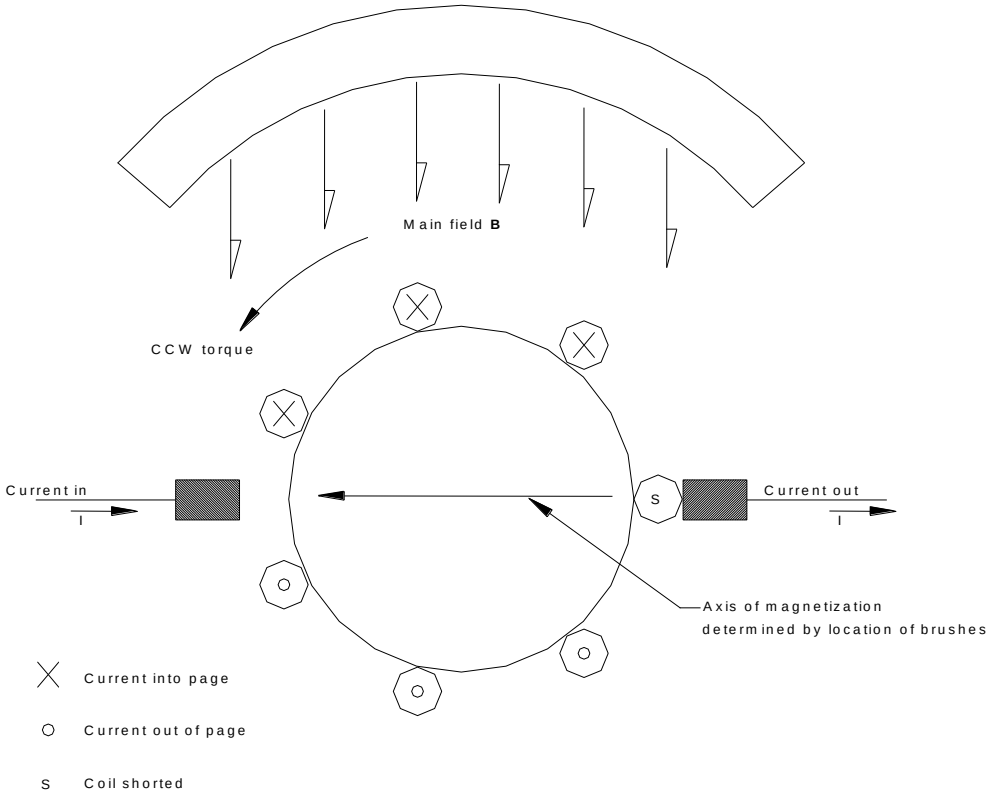

Figure (8)- Axis of magnetization

The major drawback of a brush-type motor design is the nature of the design itself. The commutation brush, as a wear item, will eventually need to be replaced. As the brushes begin to wear, microscopic particles are released, invalidating the motor for use in a clean room environment. Also, due to the switching of the coils, some electrical arcing will occur. This rules out brush motors for explosive environments. Otherwise, brush-type motors are inexpensive, reliable, accurate machines that continue to play a role in today's industrial workplace.

Brushless Motor Fundamentals

Many motor types can be considered brushless, including stepper and AC-induction motors, but the term "brushless" is given to a group of motors that act similarly to DC-brush type motors without the limitations of a physical commutator. To review, a DC-brush motor consists of a wound rotor that can turn within the magnetic field as provided by the stator, as shown in figure (9). By including the commutator and brushes, the reversal of current is made automatically and the rotor continues to turn in the desired direction.

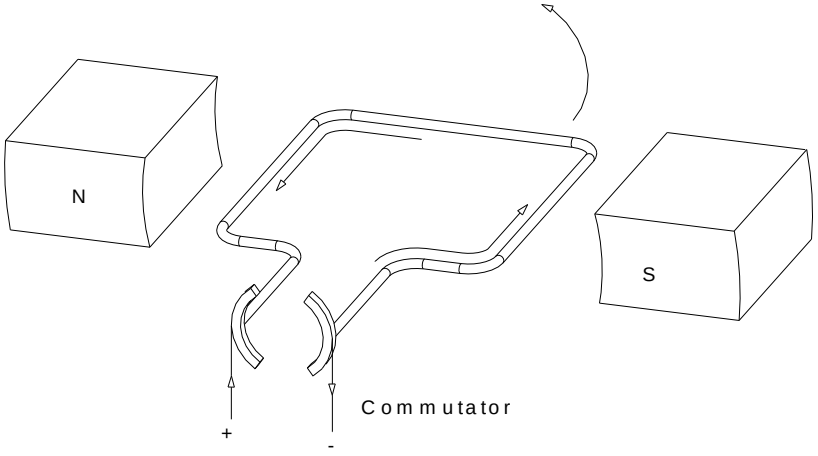

Figure (9)- A Simple brush-type motor

To build a brushless motor, the current-carrying coils must be taken off the rotating mechanism. In their place, the permanent magnet will be allowed to rotate within the case. The current still needs to be switched based on rotary position; figure (10) shows a reversing switch is activated by a cam.

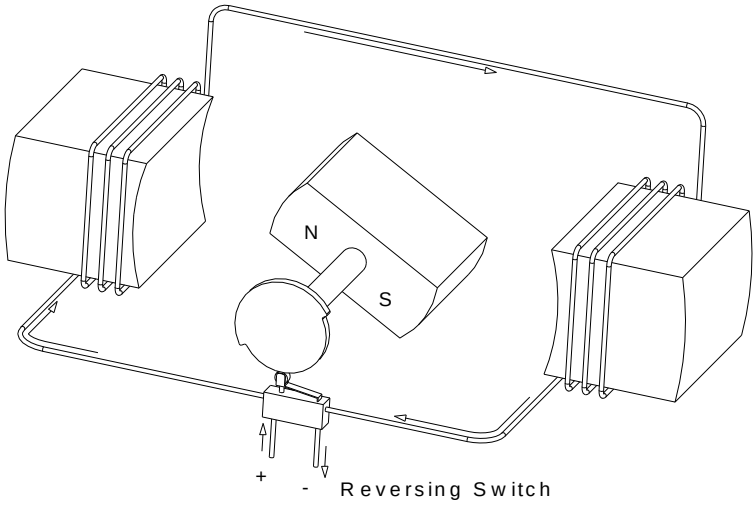

Figure (10)- An “inside-out” DC motor

This orientation follows the same basic principle of rotary motors; the torque produced by the rotor varies trapezoidally with respect to the angle of the field. As the angle θ increases, the torque drops to an unusable level. Because of this, the reversible switch could have three states: positive current flow, negative current flow, and open circuit. In this configuration, the torque based on rotary position will vary as the current is switched as shown in figure (11).

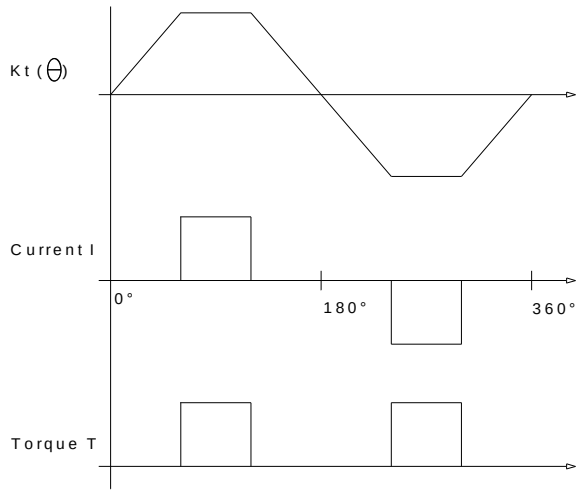

Figure (11)- Single-phase torque based on rotary position

In this model, the Torque **T** is the product of the theoretical motor constant $\mathbf{K_t}$ times the supplied current **I**. In a single pole system such as this, useable torque is only produced for 1/3 of the rotation. To produce useful torque throughout the rotation of the stator, additional coils, or "phases" are added to the fixed stator. Figure (12) shows a simple three-phase brushless motor.

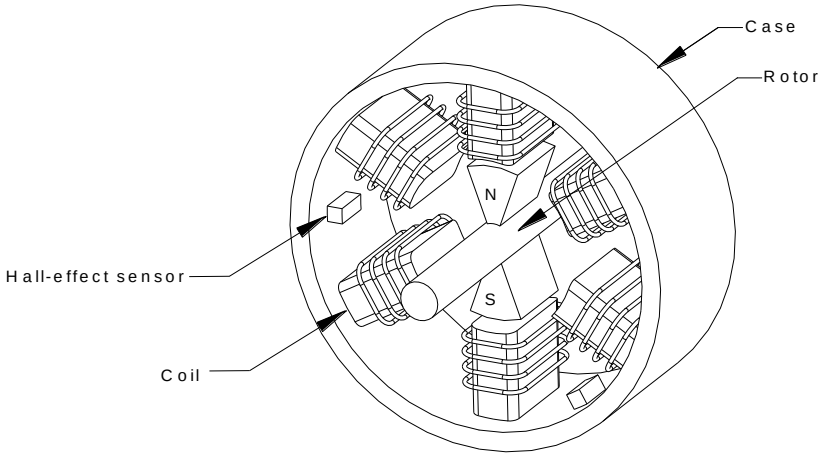

Figure (12)- Basic three-phase, 2-pole brushless motor

The key to effective motion is to switch the current in all three phases based on rotor position. The use of a physical switch is prohibited because of the timing requirements. Instead, a digital device known as a Hall-effect sensor is used. Typically, three Hall sensors are placed at 120° apart around the case of the motor. Based on the magnetic field produced by the rotor, the combination of the three logic signals can determine the location of the rotor to within 60°. From this information, the commutator switches

current flow between phases. This keeps the stator field ahead of the rotor. The desired lead angle is 90°, but because of the limitation of having only three phases, the effective lead angle will vary between 60° and 120°. Figure (13) shows the rotor at a Hall transition point. Up until θ = 60°, the commutator causes the stator field to be oriented along vector **A**. At θ > 60°, the commutator advances the field to point **B**. The average of this field switching is therefore maintained at 90°.

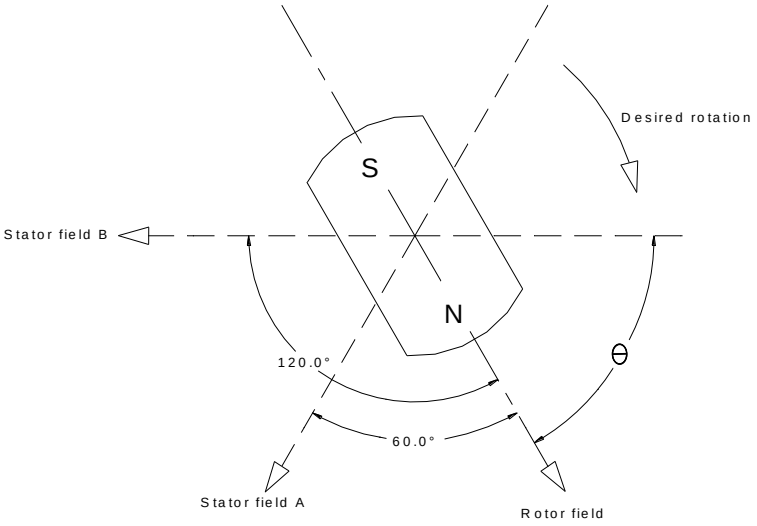

Figure (13)- Stator field orientation vs. perceived rotor location

Another aspect of the brushless motor technology is that current flows into one coil and out another. The direction of the current flow is based on position, determined by the Hall-effect sensors.

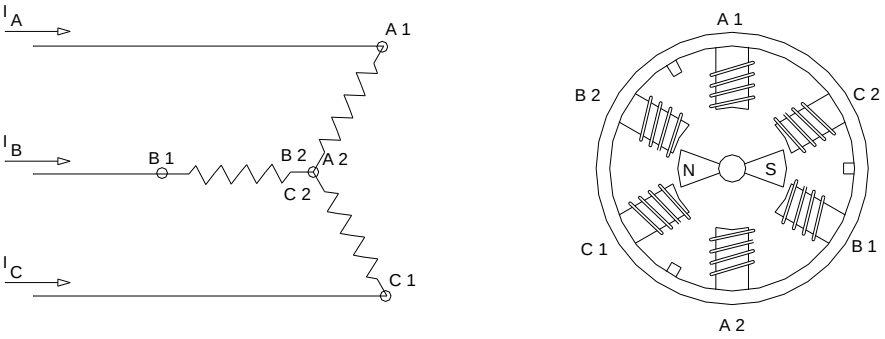

Figure (14)- 3 Phase brushless motor current schematic

It becomes apparent that the sum of the current flowing into and out of the system must be zero; thus, if I_A is positive, either I_B or I_C must be negative. Figure (15) details the relationship between the Hall-effect sensors, the subsequent switching of current in the coils, and the resultant applied torque.

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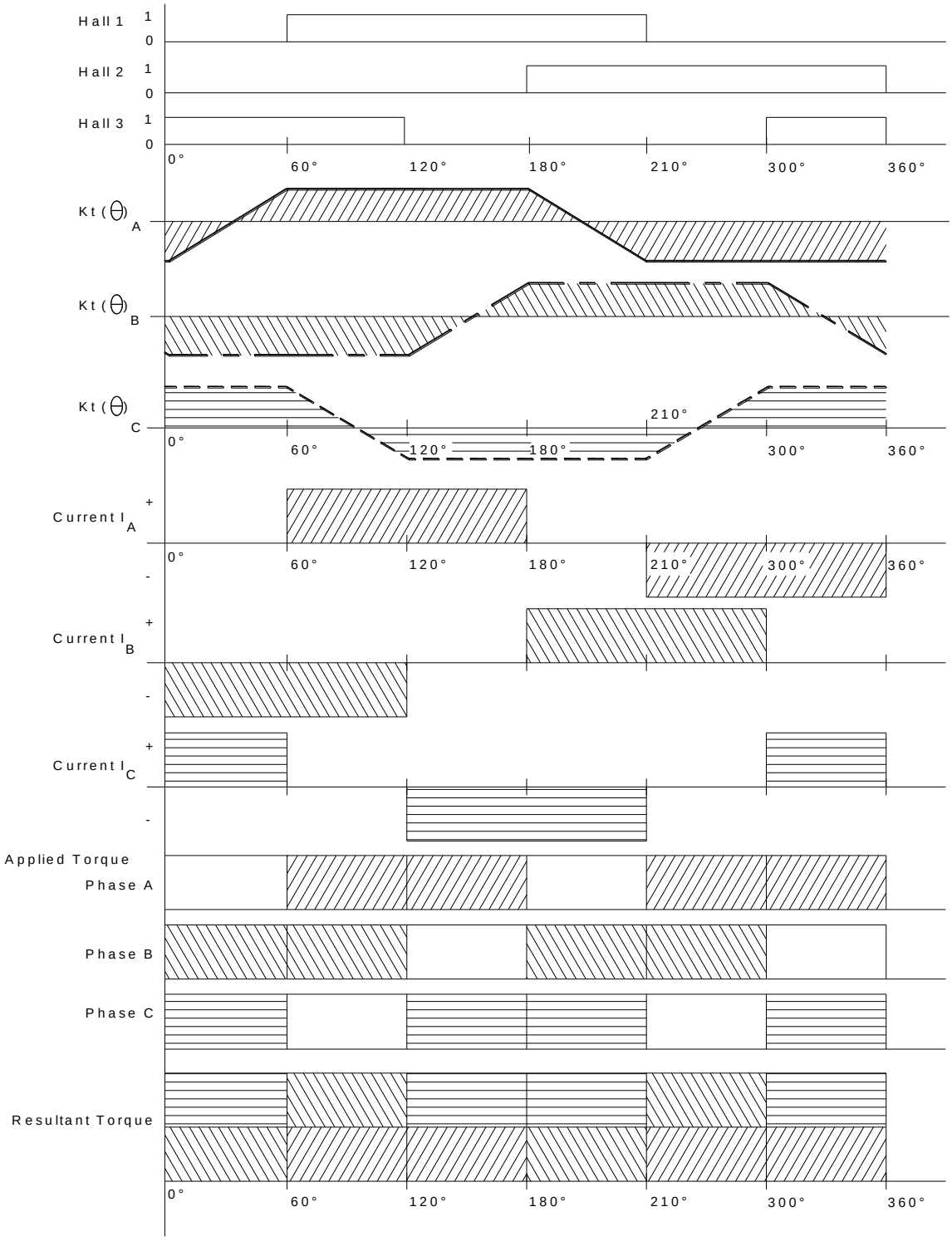

Figure (15)- Resultant torque based on position

As can be seen, the digital state of the three Hall-effect sensors can determine the rotor position within 60 degrees. For example, a reading is taken where Hall 1= high (1), Hall 2= low (0) and Hall 3= high (1). This combination 101 places the rotor at $60° < \theta < 120°$. This being true, the commutator sets the current flow into phase A (positive current) and out of phase B (negative current). The applied torque by each phase is the product of the motor constant $\mathbf{K_t}$ and the current **I**. At $60° < \theta < 120°$,

$$\mathbf{K_{t(A)}} \text{ (positive)} * \mathbf{I_A} \text{ (positive)} = \mathbf{T_A} \text{ (positive)}$$

$$\mathbf{K_{t(B)}} \text{ (negative)} * \mathbf{I_B} \text{ (negative)} = \mathbf{T_B} \text{ (positive)} \qquad (6)$$

$$\mathbf{K_{t(C)}} \text{ (indeterminate)} * \mathbf{I_B} \text{ (zero)} = \mathbf{T_B} \text{ (zero)}$$

The sum of $\mathbf{T_A} + \mathbf{T_B} + \mathbf{T_C}$ is shown on the final line. For this model, assume perfect symmetry in the phases,

$$\mathbf{K_{t(motor)}} = \mathbf{K_{t(A)}} = \mathbf{K_{t(B)}} = \mathbf{K_{t(C)}}$$

$$\mathbf{I_{motor}} = \mathbf{I_A} = \mathbf{I_B} = \mathbf{I_C} \qquad (7)$$

At any given angle θ, the applied torque as measured on the rotor shaft is

$$\mathbf{T_{motor}} = 2 * \mathbf{K_{t(motor)}} * \mathbf{I_{motor}} \qquad (8)$$

However, in a real system, the impedances of the coils will most certainly differ, albeit slightly. The motor constant and applied current can vary by several percent and still be within manufacturer's tolerance. As a test, consider that every parameter is perfect with the exception of the motor constant on phase C. As such, at certain points, the resultant torque will vary similar to Figure (16).

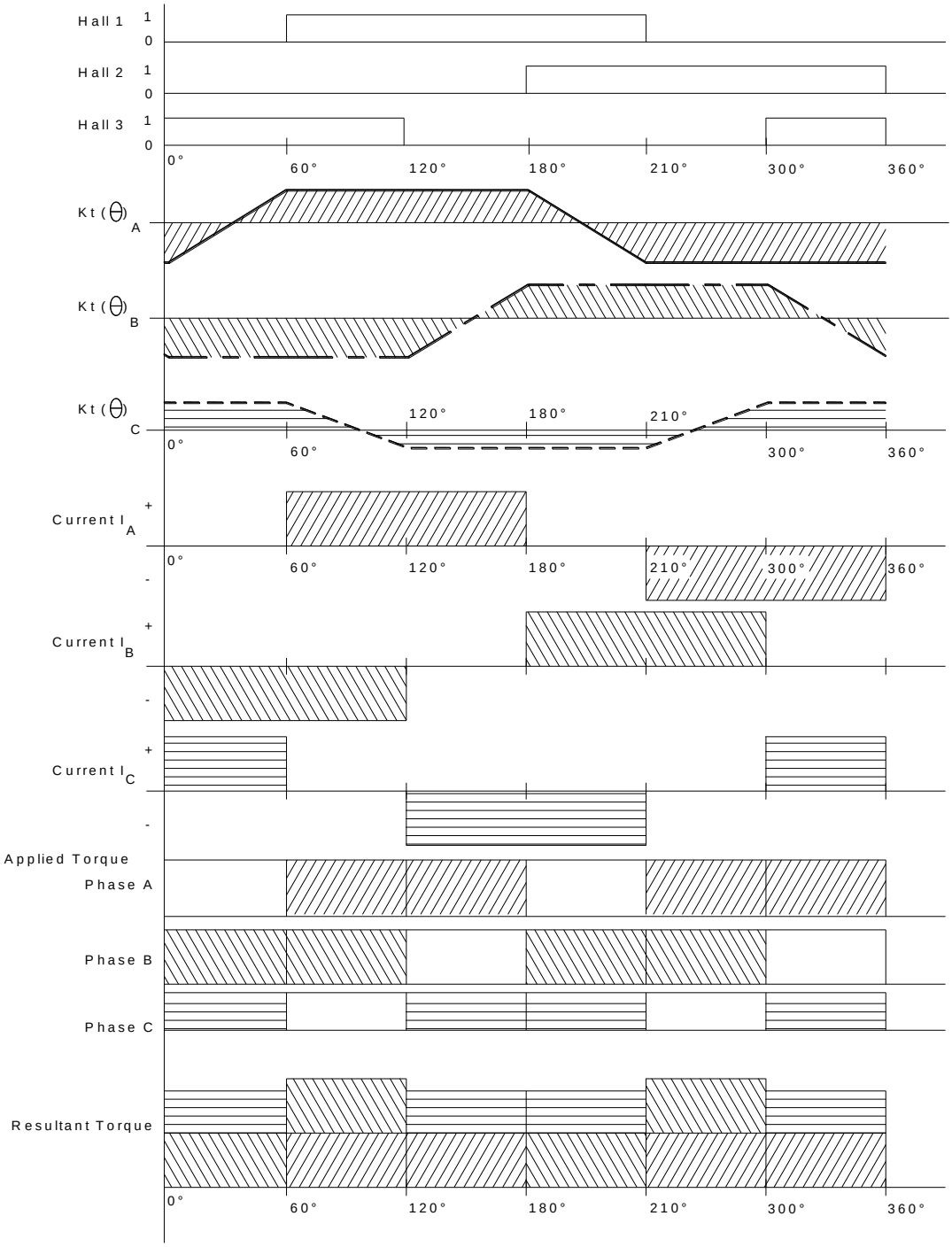

Figure (16)- Resultant shaft torque with a weak phase C

This phenomenon is commonly known as *torque ripple,* and is most noticeable at low speeds.

If a brushless motor relies on the state of Hall-effect sensors to commutate the phases, the current flowing in a coil can have three discreet states. Current can flow into the coil, out of the coil, or no current can flow. The general form of the equation for torque with respect to rotor position within the magnetic field is

$$T_A = I_A * K_{t(A)} * \sin\theta \quad (9)$$

If the position of the rotor is 90°, the supplied current is completely converted into shaft torque. As the rotor position moves away from 90°, the θ term diminishes the overall available torque. As shown earlier, the state of the current I_A will change at θ=60°. But at θ=60°, the torque is $I_A * K_{t(A)} *$ 0.866. This states that only 87% of the current is utilized. The current not converted into torque is wasted as heat.

Sinusoidal Commutation of a Brushless Motor

To fully optimize the conversion of current into shaft torque, the amplifier needs to vary the applied current **I** based on a precise measurement of θ. The torque equation for the three phases becomes

$$T_A = I_A * K_t * \sin\theta$$

$$T_B = I_B * K_t * \sin(\theta+120) \quad (10)$$

$$T_C = I_C * K_t * \sin(\theta + 240)$$

A feedback device such as a quadrature encoder can determine θ in terms of counts; a common resolution is 360° (1 revolution) = 4000 counts. The amplifier varies the current in each phase **I** based on the motor command signal **M** with respect to θ:

$$I_A = M * \sin\theta$$

$$I_B = M * \sin(\theta+120) \quad (11)$$

$$I_C = M * \sin(\theta + 240)$$

The total perceived shaft torque **T** is

$$T = T_A + T_B + T_C \quad (12)$$

Or

$$T = [I_A * K_t * \sin\theta] + [I_B * K_t * \sin(\theta+120)] + [I_C * K_t * \sin(\theta + 240)] \quad (13)$$

Substituting Eq.(11) into Eq.(13),

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$$\mathbf{T} = [\{\mathbf{M} * \sin\theta\} * \mathbf{K_t} * \sin\theta] + [\{\mathbf{M} * \sin(\theta+120)\} * \mathbf{K_t} * \sin(\theta+120)]$$

$$+ [\{= \mathbf{M} * \sin(\theta + 240)\} * \mathbf{K_t} * \sin(\theta + 240)] \quad (14)$$

reorganizing,

$$\mathbf{T} = \mathbf{K_t} * \mathbf{M} * [\sin^2\theta + \{\sin^2(\theta + 120)\}$$

$$+ \{\sin^2(\theta + 240)\}] \quad (15)$$

Using Trigonometry and canceling terms,

$$\mathbf{T} = \mathbf{K_t} * \mathbf{M} * [1.5 \sin^2\theta + 1.5 \cos^2\theta] \quad (23)$$

From Trigonometry,

$$\sin^2\theta + \cos^2\theta = 1 \quad (24)$$

Eq. (23) becomes

$$\mathbf{T} = 3/2 * \mathbf{K_t} * \mathbf{M} \quad (25)$$

For a full derivation, refer to Appendix A. Equation (25) states that the torque supplied to the rotor shaft is no longer a function of rotor angle. Torque ripple is all but eliminated and the system has linear characteristics quite similar to a conventional DC brush motor.

The calculation of torque based on rotary position assumes an ideal machine. The position θ is read and the calculated current **I** to be supplied occur at exactly the same instant. Because this system is subject to physical reality, it is important to understand the effect of an inaccurate position read due to the inherent lag in the system. Equation (11) has an additional term ϵ, defined as the angular offset in the position.

$$\mathbf{I_A} = \mathbf{M} * \sin(\theta + \epsilon)$$

$$\mathbf{I_B} = \mathbf{M} * \sin(\theta + \epsilon + 120) \quad (26)$$

$$\mathbf{I_C} = \mathbf{M} * \sin(\theta + \epsilon + 240)$$

ϵ can be an undesired offset such as physical motor lag. An error in the initial motor setup can introduce ϵ into the commutation sequence. ϵ can also be beneficial; an intentional phase advance can allow a motor to turn at marginally higher speeds. Some interesting facts about ϵ:

1. ϵ does not cause torque ripple, only torque reduction.

2. If $|\epsilon|$ < 10°, the effect on the torque is minimal. This makes the initial phase positioning non-critical.

3. When ϵ is very large (>60°), K_t is cut in half. (Cos 60°=0.5) For the motor to perform a specified amount of work, it will require twice the current. Power dissipation will increase 4X. This situation will probably burn the motor. A thermal sensor is a good safeguard against overheating.

4. If ϵ =90°, there will be zero torque. Current draw will be normal, but all the energy is converted to heat. A burned motor is a near certainty.

5. If 90° < ϵ < 270°, the polarity of the current is reversed. Positive feedback and wild oscillations will occur.

Working Eq. (26) through,

$$\mathbf{T} = 3/2 * \mathbf{K_t} * \mathbf{M} * \cos \epsilon \qquad (27)$$

This shows that ϵ values over 15° cause a drastic decrease in the available torque. To compensate, the motor will draw excessive current and could burn the motor. At very high values of ϵ, the motor can actually overdrive the circuitry and enter a mode called positive feedback. Such a state can cause catastrophic failure.

In any given system, the perceived lag will increase as the angular velocity increases. An intelligent drive system can force ϵ into a slightly positive state, much as the vacuum advance on an automobile distributor accounts for mistimed spark plug charge due to high RPM.

As with trapezoidal, a sinusoidal commutation amplifier relies on the torque constant K_t being identical in all phases. Rarely is this absolutely true; to minimize any torque ripple, most drives allow a user to vary the amplitude or offset of one or more phases.

Methods of Sinusoidal Commutation

There are two common methods of varying the current supplied to the motor windings. The historical method has relied on the amplifier to divide the current based on feedback and supply the motor, as shown in figure (17):

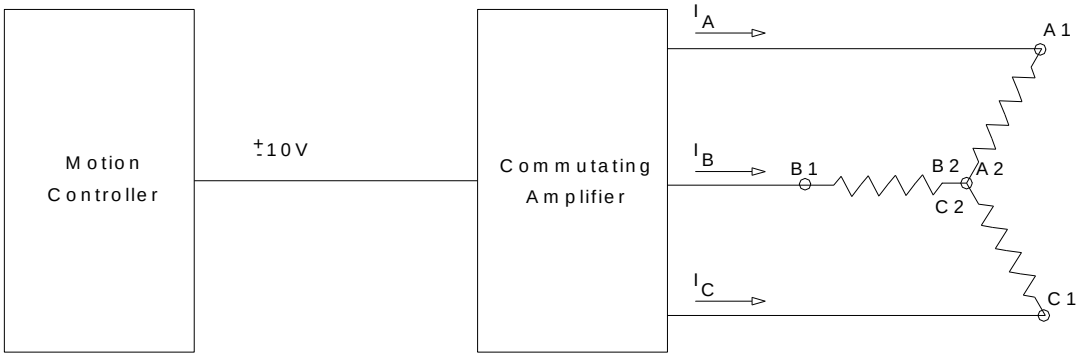

Figure (17)- A Commutating amplifier

The benefits of this method of commutation are:

- Ease of setup- simply apply a motor command signal
- No initialization needed- the amp commutates based on Hall state

The disadvantages are:

- Lack of flexibility- the amp and motor are usually paired; a brushless motor with a different commutation cycle or Hall angles render the amplifier incompatible
- Difficult to tune - If there is an offset in one or more of the phases, quite often the only method to equalize phases is a potentiometer
- The amplifier may contain a velocity loop. This effect may interfere with the operation of the controller, and must be taken into account during axis tuning

The second method involves using the motion controller to commutate the first two phases and allowing the amplifier to determine the value of the third phase. Since the sum of the currents at any time is zero, the current in the third phase equals the inverse of the sum of the currents I_a and I_b.

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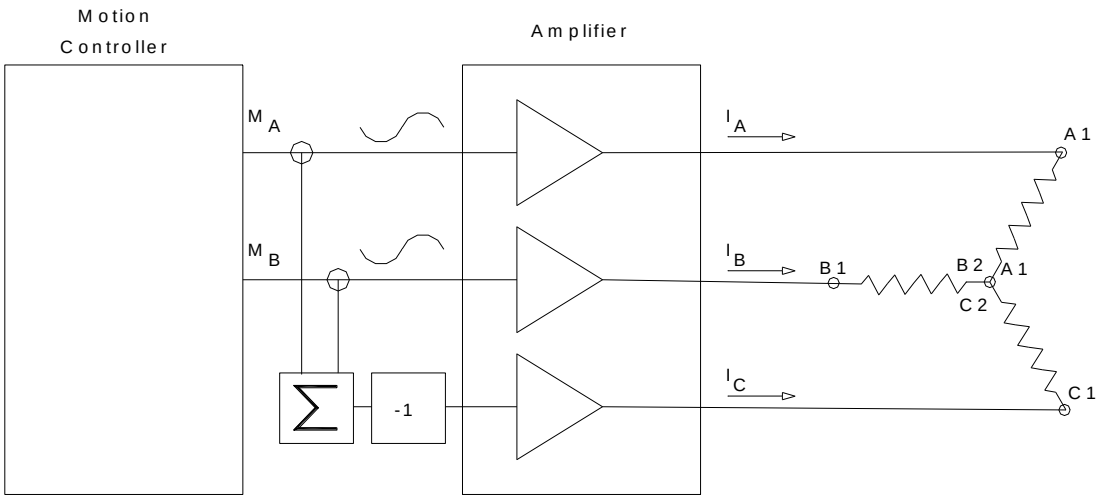

Figure (18)- Commutation by motion controller

The advantages of controller commutation are:

- The motion controller can control phase advance, offset, and commutation cycle. This flexibility allows far greater options for motor and amplifier combinations

- All control loop gains are calculated on the controller; this allows for single-point tuning

The disadvantages are:

- The commutation of two phases requires two analog output signals. On many motion controllers, this requires a second axis for each brushless amplifier, increasing the cost of the controller

- A brushless setup routine is required for the controller to determine the phasing

Regardless of the method of sinusoidal commutation, a brushless servo motor can fulfill environmental and performance specifications that simple brush-type servo motors cannot.

Part Two: Commutation Using a Galil Controller

Galil controllers produce sinusoidal motor signals by varying the commanded voltage with respect to position. The shape of the motor command voltage is a sine wave with a period equal to one brushless cycle. A brushless cycle is the number of encoder counts that separate identically charged magnetic pole pairs. If it was known that a motor is a four pole pair motor, and there are 4000 encoder counts per revolution, then there are 1000 encoder counts per magnetic cycle. The second phase of the command signal is

simply offset by 120 degrees. The third phase, which is the inverse of the sum of the first two phases, is usually determined by the amplifier.

Before the Galil controller is able to perform this commutation, a minimum of three setup commands must be given. The first indicates what axis is to be commutated as brushless, the second command sets the brushless modulus, and the third defines the 0° position. From there, the Galil controller is able to commutate based on the incoming encoder feedback.

Brushless phase resolution and frequency

If the Galil controller has the servo update time (TM) set to the default 1000 microseconds, the Galil updates the motor command signal every 1 ms. The bare minimum number of points necessary to define a sine wave is four. This leads to the limitation that, with TM1000, the brushless cycle must take at least 4 milliseconds to complete.

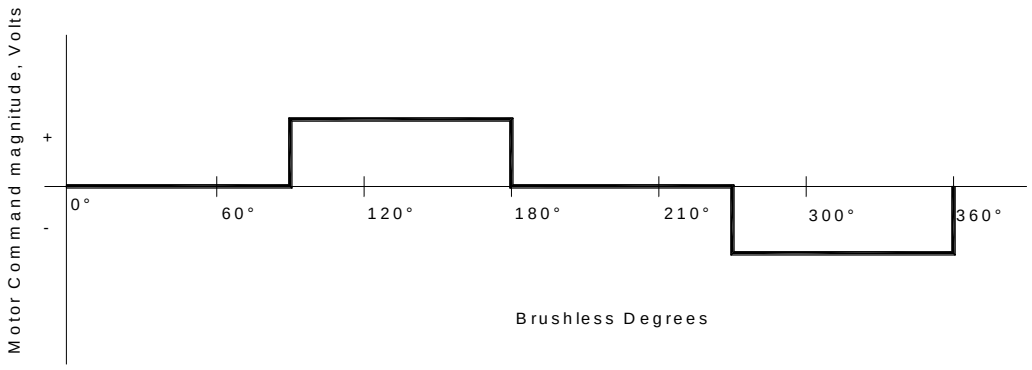

Figure (19a)- 4 point commutation

However, for smoother commutation, the user has the ability to lower the TM value. This is not without drawbacks, but can quickly lead to a much smoother sine wave at a given motor frequency. Figure (19b) shows the command voltage based on an update time of 500 microseconds.

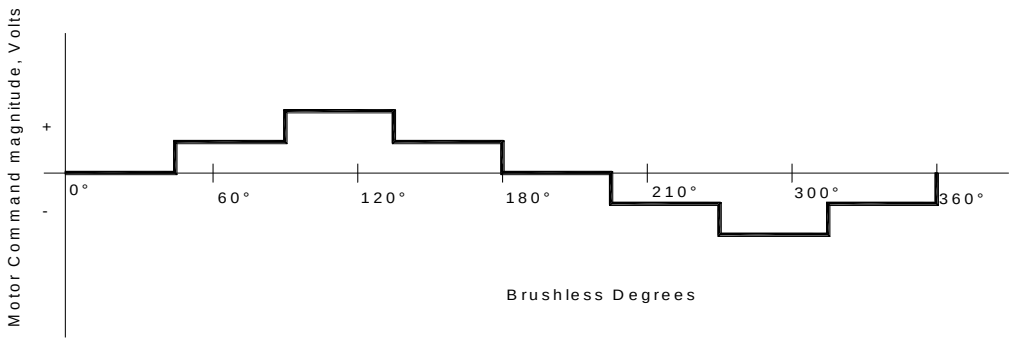

Figure (19b)- 8 point commutation

Often, the critical factor in determining the maximum frequency of the sinusoidal output will be determined by the voltage that is supplied to the amplifier. The voltage usually defines the maximum rpm of the motor. Figures (20a) and (20b) show a drastic difference between a Galil controller at TM1000 and the amplifier at 24 Volts vs. the Galil at TM125 and the amplifier at 48 Volts.

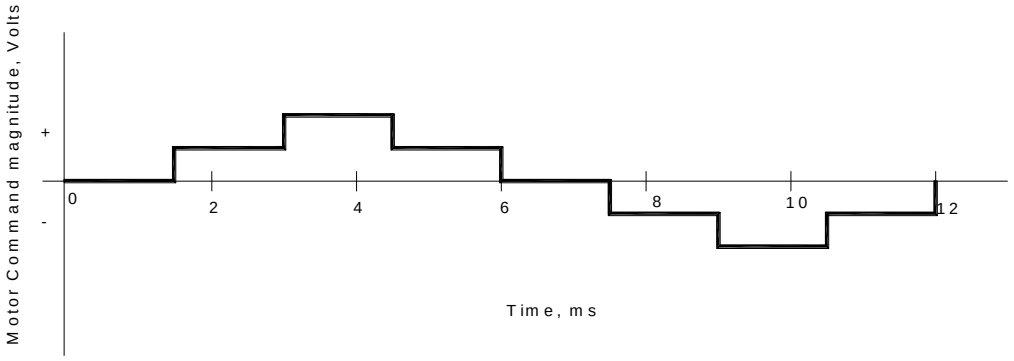

Figure (20a)- TM1000, 24 Volt power supply

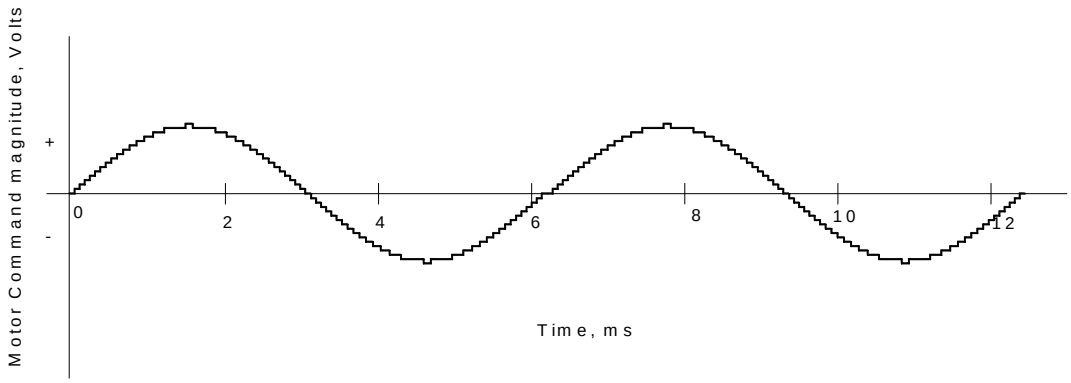

Figure (20b)- TM125, 48 Volt power supply

The user will want to balance the number of points necessary for smooth motion on the specific system with the command processing time. System inertia, motor velocity, and overall loop gain play an important role in determining the minimum TM value that is required. Note that changing the TM value requires recalibration of almost all parameters; speed, acceleration, derivative gain and many others are functions of the TM value. For Galil commutation specifications, see Appendix B.

Hardware Setup

Motor Command signal- As mentioned before, the Galil requires two analog voltage signals per sinusoidal axes. These signals, labeled MOCMDn, are wired into the amplifier's Command Voltage In.

Encoder feedback- Just as with a standard brush-type servo, the encoder signals are required for the Galil to command motion. Encoder feedback is also required for the Galil to properly commutate the sinusoidal brushless motor command signal.

Hall-effect inputs- The Hall-effect sensors are used in many motors to determine the physical location of the brushless 0°. The Hall-effects are usually offset at 0°, 30°, or 90°. If the offset is not known, it can be determined during the brushless setup. Hall-effect sensors are not required for accurate commutation.

Galil Brushless Commands

The following is a complete list of the Galil commands relating to the setup and operation of a brushless axis.

BA (Brushless Axis): The BA command configures the controller axes for sinusoidal commutation and reconfigures the controller to reflect the actual number of motors that can be controlled. Each sinusoidal commutation axis requires 2 motor command signals. The second motor command signals will always be associated with the highest axes on the controller. For example a 3 axis controller with X and Z configured for sinusoidal commutation will require 5 command outputs (5 axes controller), where the second outputs for X and Z will be the W and E axes, respectively.

BB (Brushless Phase Begins): The BB function describes the position offset between the Hall transition point and $\theta = 0$, for a sinusoidally commutated motor. This command must be saved in non-volatile memory to be effective upon reset. If no Hall-effect sensors are present, this command is not necessary.

BC (Brushless Calibration): The function BC monitors the status of the Hall sensors of a sinusoidally commutated motor, and resets the commutation phase upon detecting the first hall sensor. This procedure replaces the estimated commutation phase value with a more precise value determined by the hall sensors. If no Hall-effect sensors are present, this command is not necessary.

BD (Brushless Degrees): This command sets the commutation phase of a sinusoidally commutated motor. When using Hall-effect sensors, a more accurate value for this parameter can be set by using the command, BC. The user can query the current brushless degree value by issuing a BD? . This command should only be used when the user is creating a specialized phase initialization procedure.

BI (Brushless Inputs): The command BI is used to define the inputs that are used when Hall sensors have been wired for sinusoidally commutated motors. These inputs can be the general use inputs (bits 1-8), the auxiliary encoder inputs (bits 81-96), or the extended I/O inputs (bits 17-80). The Hall sensors of each axis must be connected to consecutive input lines, for example: BI 3 indicates that inputs 3,4, and 5 are used for halls sensors. The brushless setup command, BS, can be used to determine the proper wiring of the hall sensors.

BM (Brushless Modulo): The BM command defines the length of the magnetic cycle in encoder counts.

BO (Brushless Offset): The BO command sets a fixed offset on command signal outputs for sinusoidally commutated motors. This may be used to offset any bias in the amplifier, or can be used for phase initialization.

BS (Brushless Setup): The command BS tests the wiring of a sinusoidally commutated brushless motor. If Hall sensors are connected, this command also tests the wiring of the Hall sensors. This function can only be performed with one axis at a time.
This command returns status information regarding the setup of brushless motors. The following information will be returned by the controller:

1. Correct wiring of the brushless motor phases.
2. An approximate value of the motor's magnetic cycle.
3. The value of the BB command (If Hall sensors are used).
4. The results of the hall sensor wiring test (If Hall sensors are used).

This command will turn the motor off when done and may be given when the motor is off.
Once the brushless motor is properly setup and the motor configuration has been saved in non-volatile memory, the BS command does not have to be re-issued. The configuration is saved by using the burn command, BN.
Note: In order to properly conduct the brushless setup, the motor must be allowed to move a minimum of one magnetic cycle in both directions.

BZ (Brushless Zero): This command drives the motor to zero magnetic phase and then sets the commutation phase to zero. This command may be given when the motor is off. Essentially, the BZ command is a combination of two earlier commands: BO and BD. If a user issues a BO of +1 unit on the first phase and –1/2 unit on the second phase, the motor should move to brushless 0°. From there, the user can issue a BD0 to define this position as zero. Creating a custom brushless zero routine may be necessary in low- or no- friction systems to avoid oscillation.

A Typical Galil Brushless Axis Setup

This section illustrates how an operator would set up a normal brushless motor. For this example, the motor is a 4 pole, three phase rotary motor with Hall-effect sensors offset 60°. The encoder is 4000 counts per revolution.

Figure 6 shows a screen shot of a typical brushless axis setup.

1. The Brushless Axis is set to Z. (**BAZ**)
2. The Brushless Input on the Z-axis is given as inputs 5,6, and 7. (**BI5**)
3. Perform the Brushless Setup and test for polarity, Hall-effects, and offsets. Here the motor is energized with a 2 Volt motor command signal for 200 milliseconds in both directions. (**BSZ=2,200**) The controller returns the statement 'Wiring from the ACMD signals to the amp is correct.' If this had stated that the wiring 'must be reversed', the operator would swap the motor command for the first phase with the motor command signal for the second phase. The statement 'The Brushless Modulus (BM) is approximately 1001' is redundant in this case. If the operator had an unknown brushless modulus, the controller returns an approximate value. The statement 'The Brushless phase offset (BB) should be set to 60°' states that the Hall-effect sensors are off set 60° from brushless zero. This information was also previously known. The statement 'Input 7 has the correct sensor wired to it' and the two

following alert the operator to a legal Hall state. If the Hall sensors were undetermined, the user could rewire based on the suggestion and retry the brushless setup.

4. The Brushless Modulus is set to 1000. (**BM,,1000**) This explicitly sets the known Brushless Modulus to 1000 counts per brushless cycle.
5. The Brushless Offset is set to 60° (**BB,,60**). As stated, the Hall effect sensors must have an offset assigned. Some motors will have offsets of 120°.
6. Drive the axis to Brushless Zero. (**BZ,,-1**) This statement drives the brushless axis to theoretical brushless 0° by hitting phase A with 1 Volt and phase B with -1/2*(phase A). A negative number causes the axis to stay in the Servo Here(SH) state.
7. Query the current Brushless Degree (**BD,,?**). The response, **2.88**, is within untuned tolerance. If this number was greater than expected, try issuing a larger voltage on the BZ command. If the motor his high friction or heavy inertia, 1 Volt may not have been enough to drive the motor to an accurate reading of brushless zero. If the system oscillates and times out, increase the BZ timeout by adding a '<n' in the second field. See the Command Reference for details.

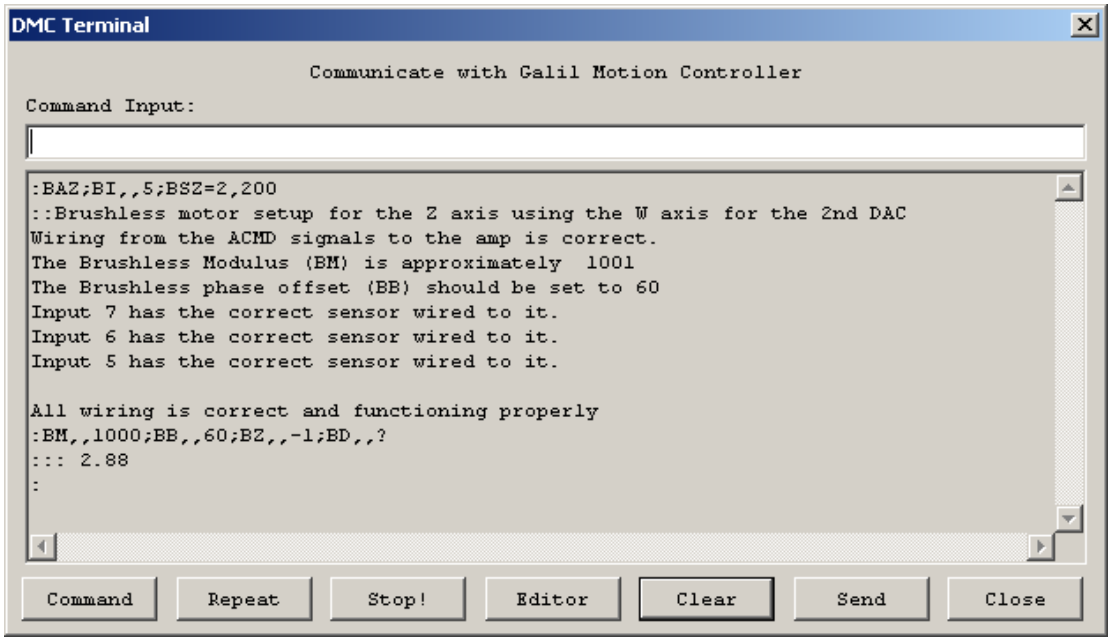
DMC Terminal
Communicate with Galil Motion Controller
Command Input:
:BAZ;BI,,5;BSZ=2,200
::Brushless motor setup for the Z axis using the W axis for the 2nd DAC
Wiring from the ACMD signals to the amp is correct.
The Brushless Modulus (BM) is approximately 1001
The Brushless phase offset (BB) should be set to 60
Input 7 has the correct sensor wired to it.
Input 6 has the correct sensor wired to it.
Input 5 has the correct sensor wired to it.
All wiring is correct and functioning properly
:BM,,1000;BB,,60;BZ,,-1;BD,,?
::: 2.88
:
Command
Repeat
Stop!
Editor
Clear
Send
Close

Figure (21)- Brushless motor setup

Part Three: Application Examples

Brushless motor technology can be found in a variety of applications, including linear motors, high-rpm air-bearing spindles, and low-speed direct drives. Included here are a few tips and tricks for setting up these systems to run with a Galil Motion Controller.

Linear Motors

Linear brushless motors are essentially a rotary motor that lays flat. The stage acts like the stator, while the case magnets are laid sequentially along the track. Setup and configuration are very similar to rotary motors, however, linear motors are capable of producing immense amount of torque, and, due to physical design, cannot run freely like a rotary motor can. Extreme caution should be taken during initialization. Ensure working limit switches, if available, before applying power to the motor. Before any commands are issued, the operator must fully understand the functions and consequences of what is typed. A common safety routine such as the following might be incorporated into an X-axis initialization:

```
:MO          'Disables amplifiers

:OF0         'Sets offset bias to zero

:KP1         'Sets proportional gain to 1

:KD5         'Sets derivative gain to 5

:KI0         'Sets integral gain to 0

:TL.5        'Sets maximum output voltage to .5 volts (5% of max)

:ER1000      'Sets error limit to 1000

:ER1         'Enable Off-on-Error function
```

**At this point, apply power to the amplifier. The motor should not move (MO)

```
:SHX         'Enable X-axis
```

**This command enables the axis. Be fully aware of any safety considerations before attempting this. After the axis is enabled, the stage should not move. The TE (Tell Error) command should return a reasonable amount of error. If the stage jumped, check the error. If it is greater than 1000(in this case) the axis ran away until the Off-on-Error shut the axis down. Check encoder polarity, noise, or dead shorts. Once the motor remains stable, the user is ready to perform the standard brushless motor setup as discussed previously.

Air-bearing Spindles

Spindle motors are commonly used at very high velocity. 10,000 rpm is not an uncommon requirement. Some thought is necessary to ensure appropriate commutation at these speeds. As discussed in Section 2, decreasing the TM value can markedly increase sinusoidal resolution. Note that all time-based commands will have their apparent values modified if the TM is not default. To calculate the maximum rpm and counts/second, apply the following equations:

Max Rotational Velocity (RPM):

$$X\ (RPM\ ) = \frac{60\ \text{sec}}{1\ \text{min}} * \frac{1000\ \ m\ \text{sec}}{1\ \text{sec}} * \frac{1 magnetic\ \ \_\ cycle}{(\#\ of\ \ \_\ desired\ \ \_\ samples\ )} * \frac{1\ \text{Re}\ v}{\#\ of\ \ \_\ mag\ \ \_\ cycles} * \frac{1}{TM\ \ (\mu\ \text{sec})} * \frac{1000\ \ \mu\ \text{sec}}{1 m\ \text{sec}}$$

$$X\ (RPM\ ) = \frac{6 * 10^{7}}{(\#\ mag\ \ \_\ cycles\ \ / rev\ ) * (TM\ ) * (\#\ of\ \ \_\ desired\ \ \_\ samples\ )} \qquad (28)$$

Max Commanded Velocity:

$$\max\_\ \ velocity\ \left(\frac{counts}{\text{sec}}\right) = \frac{(\#\ counts\ \ / mag\ \ \_\ cycle\ ) * 10^{6}}{TM\ \ * (\#\ desired\ \ \_\ samples\ )} \qquad (29)$$

Air bearings, with their minimal inherent friction, present a somewhat unique dilemma when initializing the axis. The BZ command relies on friction to damp out the motion before the command times out. If the axis constantly times out, increase the timeout value with the <t argument. Refer to the Command Reference for details. If the axis still does not settle, investigate a velocity-based damping algorithm to minimize overshoot during the axis setup. Refer to Application Note 3413 for an example of such an operation.

Low-Speed Direct Drives

Direct-drive designs can minimize components, mechanical play, and harmonic resonance. However, at lower speeds, a brushless motor can display “torque ripple”, an effect of imprecise phasing and the quantizing of the phase signal. Higher-end motors minimize this effect. If a design does exhibit a noticeable velocity ripple at slow speeds, the operator might consider two things: lower the PID settings to 75% of their original values. Does this improve or exacerbate the situation? A second and more drastic step is to increase the TM value, making the servo update time larger. Again, keep in mind the TM value affects almost all the system parameters. If torque ripple is still present, the specified amplifier may be insufficient for the requested mode of operation.

Conclusion

Galil Motion Controllers provide a robust, firmware-level brushless servo motor control as an alternative to amplifier-based commutation. This functionality can be integrated into an innumerable variety of industrial applications. If a particular aspect of brushless implementation proves elusive, the Applications Department at Galil is more than willing to assist.

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Appendix A

Complete derivation of shaft torque based on rotor position

To fully optimize the conversion of current into shaft torque, the amplifier needs to vary the applied current **I** based on a precise measurement of θ. The torque equation for the three phases becomes

$$\mathbf{T_A} = \mathbf{I_A} * \mathbf{K_t} * \sin\theta$$

$$\mathbf{T_B} = \mathbf{I_B} * \mathbf{K_t} * \sin(\theta+120) \quad (10)$$

$$\mathbf{T_C} = \mathbf{I_C} * \mathbf{K_t} * \sin(\theta + 240)$$

A feedback device such as a quadrature encoder can determine θ in terms of counts; a common resolution is 360° (1 revolution) = 4000 counts. The amplifier varies the current in each phase **I** based on the motor command signal **M** with respect to θ:

$$\mathbf{I_A} = \mathbf{M} * \sin\theta$$

$$\mathbf{I_B} = \mathbf{M} * \sin(\theta+120) \quad (11)$$

$$\mathbf{I_C} = \mathbf{M} * \sin(\theta + 240)$$

The total perceived shaft torque **T** is

$$\mathbf{T} = \mathbf{T_A} + \mathbf{T_B} + \mathbf{T_C} \quad (12)$$

Or

$$\mathbf{T} = [\mathbf{I_A} * \mathbf{K_t} * \sin\theta] + [\mathbf{I_B} * \mathbf{K_t} * \sin(\theta+120)] + [\mathbf{I_C} * \mathbf{K_t} * \sin(\theta + 240)] \quad (13)$$

Substituting Eq.(11) into Eq.(13),

$$\mathbf{T} = [\{\mathbf{M} * \sin\theta\} * \mathbf{K_t} * \sin\theta] + [\{\mathbf{M} * \sin(\theta+120)\} * \mathbf{K_t} * \sin(\theta+120)]$$

$$+ [\{= \mathbf{M} * \sin(\theta + 240)\} * \mathbf{K_t} * \sin(\theta + 240)] \quad (14)$$

reorganizing,

$$\mathbf{T} = \mathbf{K_t} * \mathbf{M} * [\sin^2\theta + \{\sin(\theta + 120) * \sin(\theta + 120)\}$$

$$+ \{\sin(\theta + 240) * \sin(\theta + 240)\}] \quad (15)$$

From trigonometry,

$$\text{Sin}(A+B) = \sin A \cos B + \cos A \sin B \quad (16)$$

Substituting Eq.(16) into portions of Eq.(15)

$$\sin(\theta + 120) * \sin(\theta + 120) = (\sin\theta \cos 120 + \cos\theta \sin 120) * (\sin\theta \cos 120 + \cos\theta \sin 120) \quad (17)$$

and

$$\sin(\theta + 240) * \sin(\theta + 240) = (\sin\theta \cos 240 + \cos\theta \sin 240) * (\sin\theta \cos 240 + \cos\theta \sin 240) \quad (18)$$

applying F-O-I-L and adding numeric values to Eq. (17) and (18):

$$\sin(\theta + 120) * \sin(\theta + 120) = .25 \sin^2\theta + (-.5\sin\theta)(.866\cos\theta) + (-.5\sin\theta)(.866\cos\theta) + .75\cos^2\theta \quad (19)$$

and

$$\sin(\theta + 240) * \sin(\theta + 240) = .25 \sin^2\theta + (-.5\sin\theta)(-.866\cos\theta) + (-.5\sin\theta)(-.866\cos\theta) + .75\cos^2\theta \quad (20)$$

substituting Eq. (19) and (20) back into Eq. (15):

$$\mathbf{T} = \mathbf{K_t} * \mathbf{M} * [\sin^2\theta + .25 \sin^2\theta + (-.5\sin\theta)(.866\cos\theta) + (-.5\sin\theta)(.866\cos\theta) + .75\cos^2\theta + .25 \sin^2\theta + (-.5\sin\theta)(-.866\cos\theta) + (-.5\sin\theta)(-.866\cos\theta) + .75\cos^2\theta \quad (21)$$

canceling terms:

$$\mathbf{T} = \mathbf{K_t} * \mathbf{M} * [\sin^2\theta + .25 \sin^2\theta + .75\cos^2\theta + .25 \sin^2\theta + .75\cos^2\theta \quad (22)$$

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And

$$\mathbf{T} = \mathbf{K_t} * \mathbf{M} * [1.5 \sin^2\theta + 1.5 \cos^2\theta] \quad (23)$$

From Trigonometry,

$$\sin^2\theta + \cos^2\theta = 1 \quad (24)$$

Eq. (23) becomes

$$\mathbf{T} = 3/2 * \mathbf{K_t} * \mathbf{M} \quad (25)$$

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Appendix B

Galil Optima Series Controller commutation specifications

Number of axes	Time step	Brushless cycle	# of points
1-8	TM1000	4 ms	4
7-8	TM625	4 ms	6
7-8	TM500*	2 ms	4
5-6	TM500	4 ms	8
5-6	TM375*	4 ms	10
3-4	TM375	2 ms	5
3-4	TM250*	4 ms	12
1-2	TM250	2 ms	6
1-2	TM125*	4 ms	24

* Indicates Fast Firmware

References

1. *DC Motors, Speed Controls, Servo Systems* , Various authors. Electro-Craft Corporation, Hopkins, MN 55343. pp 2.1-2.37 & 6.1-6.21

2. *Command Reference, Optima Series*, Various authors. Galil Motion Control, Rocklin, CA 95765

3. *User Manual, Optima Series*, Various authors. Galil Motion Control, Rocklin, CA 95765. pp 2.20-2.22 & A175-A177